AD

AD 738843

TECHNICAL REPORT

WVT-7166

INELASTIC BEHAVIOR OF THICK-WALL CYLINDERS

Approved for public release; distribution unlimited.

DECEMBER 1971

BENET R&E LABORATORIES

WATERVLIET ARSENAL

WATERVLIET—NEW YORK

AMCMS No. 501B.11.85800.02

DA Project No. 1T061102B33A01

DISPOSITION

Destroy this report when it is no longer needed. Do not return it to the originator.

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Watervliet Arsenal Watervliet, N.Y. 12189	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

INELASTIC BEHAVIOR OF THICK WALL CYLINDERS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

John D. Vasilakis

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1971	28	3

8a. CONTRACT OR GRANT NO. AMCMS No. 501B.11.85400.02 b. PROJECT NO. DA Project No. 1T061102B33A01 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) WVT-7166 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Weapons Command

13. ABSTRACT

Thick-walled cylinders were tested under pressure for various end conditions. The two materials used were annealed copper and C1045 steel in the annealed condition. Pressurization continued until the tubular specimens were fully plasticized, i.e. uncontained plastic flow had occurred Tests were conducted with the specimens in the open end, closed end and closed end with an applied axial load position. Material properties were also derived experimentally with the use of tensile specimens and thin-walled cylinders. The modulus of elasticity, Poisson's ratio and the strain hardening factor were found for each material.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plastic Deformation						
Thick-Wall Cylinders						
Strain Hardening						

Unclassified

Security Classification

AD

TECHNICAL REPORT

WVT-7166

INELASTIC BEHAVIOR OF THICK-WALL CYLINDERS

BY

JOHN D. VASILAKIS

Approved for public release; distribution unlimited.

DECEMBER 1971

BENET R&E LABORATORIES

WATERVLIET ARSENAL

WATERVLIET—NEW YORK

AMCMS No. 501B.11.85800.02

DA Project No. 1T061102B33A01

INELASTIC BEHAVIOR OF THICK-WALL CYLINDERS

ABSTRACT

Thick-walled cylinders were tested under pressure for various end conditions. The two materials used were annealed copper and C1045 steel in the annealed condition. Pressurization continued until the tubular specimens were fully plasticized, i. e. uncontained plastic flow had occurred. Tests were conducted with the specimens in the open end, closed end and closed end with an applied axial load position. Material properties were also derived experimentally with the use of tensile specimens and thin-walled cyl[illegible] [illegible] modulus of elasticity, Poisson's ratio and the strain hardening factor were found for each material.

Cross Reference Data

Plastic Deformation

Thick-Wall Cylinders

Strain Hardening

TABLE OF CONTENTS

TABLE

FIGURES

DEFINITION OF SYMBOLS

E Modulus of elasticity

ν Poisson's Ratio

α Strain hardening factor (as computed from uniaxial tests)

$\bar{\alpha}$ Strain hardening factor (as computed from effective stress-effective strain results)

σ_e Yield stress in tension

$\bar{\sigma}$ Effective stress

$\bar{\epsilon}$ Effective strain

INTRODUCTION

An experimental test program for pressurizing thick-walled cylinders under various end conditions has been conducted. The end conditions considered were open end, closed end, and closed end with an applied axial load. A single test fixture was designed and fabricated which accommodated all three end conditions. This will be described later. A dead weight tester with a 100000 psi capacity was used to pressurize the specimen and a Universal Testing Machine was used to support the fixture and supply the axial load. In test, the thick-walled cylinders were pressurized until they were in a fully plastic condition. Two materials were used, an annealed copper and an annealed C1045 steel. Tensile specimens and thin-walled tubes were used to determine material properties. The modulus of elasticity, E, Poisson's ratio, ν, and the strain hardening factor, α, defined by[(1),(3)] either

$$\bar{\sigma} = \sigma_e (1 - \bar{\alpha}) + \bar{\alpha} E \bar{\varepsilon} \qquad (1)$$

or

$$\sigma_z = \sigma_e (1 - \alpha) + \alpha E \varepsilon_z$$

were determined for each material.

APPARATUS

(a) Test Fixture

A drawing of the test fixture is shown in Figure 1. The section shows the various components of the apparatus and how the different end conditions are accomplished. The specimen has an outer diameter of 1.5

1. Chu, Shih-Chi, Inelastic Behavior of Thick-Wall Cylinders Made of Strain Hardening Materials, Rock Island Arsenal Report RE7110, U. S. Army Weapons Command, Rock Island, Illinois.
3. Smith, J. O. and Sidebottom, O. M., Inelastic Behavior of Load-Carrying Members, John Wiley and Sons, Inc., New York, 1965.

inches and an inner diameter of 1.0 inch. Its length is 7.5 inches. The filler bar is used to take up volume in the interior so that little oil is used in pressurizing the specimen. Seal plugs butt against the filler bar and also hold the seals. Two leather packings, a rubber "O" ring, and a square aluminum seal are used on each end. The adapter and adapter nut lock against the end of the specimen and their effect depends on the end condition desired. One of the adapters and seal plugs accommodates the oil fitting for pressurization.

Hill[2] discussed the various end conditions involved. For a closed end tube, the longitudinal force is equal to the force generated by the internal pressure acting on the end plugs. This is accomplished in the fixture by removing the Universal Test Machine (UTM) adapters shown in the drawing. As internal pressure is increased, the seal plugs move out against the adapter which transmits the end load to the specimen end resulting in the required loading for a closed end specimen. In this case the test fixture sits on its end or the lower platen of the UTM. Figure 2 is a photograph of an exploded view of the apparatus and Figure 4 shows the apparatus set up in the closed end condition. For the open end configuration, the longitudinal force in the specimen is zero. This is accomplished by replacing the UTM adapters by straight unthreaded adapters which rest on the seal plugs and extend a little beyond the ends of the adapter. Thus the open-end configuration can be satisfied in two ways. The unthreaded adapters are positioned between the platens of the UTM. The internal pressure, as it is increased, acts on the seal plugs as before but this time they are prevented from contacting the adapter. They transmit the load to the unthreaded adapters which in turn act on the platens of the UTM. Here,

2. Hill, R., The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1956.

the load is carried by the UTM. Since this involved motion of the seals during pressurization, a better method of loading in the open end case was to apply an axial compressive load to the unthreaded adapters using the UTM. This applied axial load was approximately the maximum axial load expected during the test. The load was applied to the column consisting of the unthreaded adapters, the seal plugs and the filler bar. Readings on the strain gages on the specimen during this procedure rarely exceeded 10 - 15 microinches/inch showing very little seal friction. As the internal pressure was increased, little change was noted on the UTM dial reading indicating little seal motion during pressurization. Figure 3 shows the apparatus in the open end condition.

The final configuration to be tested was the closed end with applied tensile load. In this configuration the UTM adapter was threaded into the ends of the adapter and the fixture loosely held in the upper set of platens in the UTM. After the required internal pressure was reached, a tensile load was applied to the specimen through the UTM adapters. This is shown in Figure 5. The material used for the fixture is a hardened 4340 steel. The UTM is a commercially purchased test machine with a 120000 lbs capacity. Pressurization was accomplished using a dead weight tester, i. e. the internal pressure is balanced against a set of weights acting on a small piston For readings between weights, which were necessary with the copper, a calibrated load cell and a nullmeter were used.

In addition to the above tests, tensile specimens and thin walled cylinders were also tested for the purpose of determining the material properties. The tensile specimens were .507 inch diameter with threaded ends and 2 in gage length and were tested in the UTM. Thin walled

specimens were fabricated from thick walled specimens. The specimen wall thickness was .020 inches, the inside diameter remaining 1 inch.

(b) Gaging

For each thick-walled tube, two axial and two tangential strain gages were used. The gages used were 120 ohm high elongation gages with a three-eighths gage length. A high elongation epoxy, RTC, was used in bonding the gages. The same type gage was used in the thin walled specimens. For the tensile specimens, smaller high elongation gages available in the laboratory were used. These had a gage length of one-eighth inch and included two types, a single general purpose gage as well as a tee rosette gage - two grids with one 90° to the other. Gages are individually fed into a 10 channel balance unit and then to a strain indicator. Gages are individually read and then averaged if a plot of the points is required.

(c) Test Procedure

After installation of the gaged specimen in the test fixture and the UTM, all specimens are usually cycled once or twice at a low load just to insure proper gage operation. For the tensile test, the specimen is then pulled in tension maintaining the stress within the elastic range of the material. This is repeated at least once. This will supply information for computing the elastic constants. To calculate α , the strain hardening factor the output of the UTM and the two axial gages are applied to an X-Y plotter and a high elongation test is run. The elongations were mostly about 3.5%, however, using a different curing method for the cement, elongations up to 9% were achieved. It was felt that the strain hardening factor could be computed on elongations which were as yet uniform,

i. e., before necking.

Tests on the thin walled tubes for material properties were conducted in the closed end condition. Results were recorded and no attempt was made to get elastic properties as these were well established by the tensile tests. All gages were recorded individually.

Thick wall cylinder tests were done by installing the specimen in the apparatus under the desired end conditions. Gages were read individually on a strain indicator. Pressure was applied using the dead weight tester until one could no longer keep up with the readings. Hill[2] supplied an equation to be used in an autofrettage process which gives the tangential strain on the outside diameter for a fully plastic tube. Whenever this was calculated, the recorded strain exceeded the calculated one indicating that the tube had been fully plasticized.

RESULTS AND DISCUSSION

(a) Tensile Test

Several tensile specimens were tested to determine the elastic constants of the materials used. Two tangential gages and two axial gages, all high elongation, were applied to the specimen. Two steel and two copper specimens were each tested in the following manner.

A specimen is pulled in tension at load levels which do not exceed the elastic limit of the material. All gages are recorded individually using a strain indicator. This gives sufficient information for computing the modulus of elasticity, E, and Poisson's ratio, ν. To find the modulus of elasticity, the axial gage output is averaged and the best straight line is drawn through the points using the method of least squares. The technique is suggested by standard test ASTM Designation:

2. Hill, R., The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1956.

E111-61. To find Poisson's ratio, the tangential strain and axial strain are each plotted against load, again using the method of least squares to find the best straight line fit for each curve. Poisson's ratio is then found from the ratio of the slopes of the curves. This technique is suggested by ASTM Designation: E132-61.

In testing for the strain hardening factor, α, the data must be recorded continuously due to the plastic deformation occurring. Hence the two axial gages were used in a bridge circuit which fed the X axis of an X-Y Plotter. A linear potentiometer was connected to the bellows of the dial of the Universal Test Machine and its output recorded as the Y axis. From this arrangement, a direct load-strain curve of each tensile specimen was obtained. At least 3 1/2% strain was plotted before any of the gages would give way. The slope curve after the material is fully yielded is found and set equal to αE and thus α is calculated. It must be kept in mind that α, as found in this manner, is the strain hardening factor in a tensile test, i. e., the stress-strain curve in that region would be

$$\sigma_z = \sigma_e(1-\alpha) + \alpha E \varepsilon_z \tag{2}$$

If the effective stress-strain expressions are used, then from Reference (1) and (3), the same equation (2) is written

$$\bar{\sigma} = \sigma_e(1-\bar{\alpha}) + \bar{\alpha} E \bar{\varepsilon} \tag{3}$$

---

1. Chu, Shih-Chi, Inelastic Behavior of Thick-Wall Cylinders Made of Strain Hardening Materials, Rock Island Arsenal Report RE7110, U. S. Army Weapons Command, Rock Island, Illinois.
3. Smith, J. O. and Sidebottom, O. M., Inelastic Behavior of Load-Carrying Members, John Wiley and Sons, Inc., New York, 1965.

where

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2} \tag{4}$$

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_r - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_r)^2} \tag{5}$$

The $\bar{\alpha}$ calculated from Eq. (3) is the same as Eq. (2) if incompressibility is assumed, i. e., $\nu = 1/2$.

Elastic constants and strain-hardening factor for the tensile tests are shown in Table I.

During the first tensile test run, load-strain readings were taken manually as far as possible into the plastic range, the specimen unloaded and the test repeated with the output being recorded on the X-Y Plotter. The results from the X-Y Plotter are shown in Figure 6. Readings are taken from the curve and the slope and hence α calculated (see Table I). Portion of the curve used is that part after yielding is completed. As mentioned before, this α is calculated from a tensile test expression (Eq. 2) and the α would be the same as that from Eq. 3 if the material is considered incompressible.

Data and results from the first two copper tensile specimens and the first two steel tensile specimens are given in Figures 6 - 9.
Since annealed copper was thought to have some strain hardening factor, it was felt that the copper being used was not annealed but already hardened. One of the copper tensile specimens (C3) was then re-annealed in the laboratory at 600° F for 1/2 hour and water quenched. The annealing temperature was chosen low to keep any distortion of the already machined specimen

either negligible or to a minimum. Figure 10 shows the results from the X-Y Plotter during the large deformation test. Differences between these results and the others are negligible as far as the strain-hardening factor is concerned. Elongation in this case, however, was higher.

The X-Y Plotter put a limit on the number of gages that could be recorded, hence, the above results are found by using axial force versus axial strain. Thus the α is calculated for a uniaxial test rather than a multiaxial test. The two conditions give a different α as described in Reference 3 if compressibility is assumed and for the multiaxial test the effective stress-effective strain relation must be used in the computation.

Two tensile tests, one with a copper and one with a steel specimen, were repeated using a recorder to individually record the strain gages. This gave a record of the axial load and the axial and the tangential strain, allowing direct computation of $\bar{\alpha}$ from the effective stress-effective strain expression. The results of the steel specimen are shown in Figure 11 and the results from the copper specimen are shown in Figure 12.

Results for the strain hardening factor are given in Table 1. The strain hardening factor α is found from the uniaxial stress and strain data and $\bar{\alpha}$ from the computation of effective stress-effective strain. Differences between the two factors were small.

(b) Thin Wall Tests

Two thin wall tubes were tested in the closed end condition. These were to provide additional results for the determination of the material properties. The output of the gages was recorded individually. The results of these tests are given in Figures 13 and 14. Tests were

3. Smith, J. O. and Sidebottom, O. M., Inelastic Behavior of Load-Carrying Members, John Wiley and Sons, Inc., New York, 1965.

continued until the thin wall tubes burst. A strain hardening factor is given in Table 1, but the tubes burst before any large plastic flow occurred.

(c) Thick Wall Tubes

Results for the thick walled tubes are shown in Figures 15 through 18. Steel tubes #1 and #4 were tested in the open end configuration as were copper tubes #1 and #4. Steel tubes #2 and #3 and copper tubes #2 and #3 were tested in the closed end conditions. Steel tubes #5 and #6 and copper tubes #5 and #6 were tested as close ended with an applied axial load. Readings were taken as pressure was increased until it became impossible to keep up with the motion of the material. Simple calculations from Hill[2], gave the indication with regard to tangential strain that the tubes were fully plasticized. In tubes tested in closed end configuration with an applied axial load, the pressure was brought up to initially yield the bore of the tube. An axial load was then applied using the UTM while the pressure was maintained constant. In Figures 17 and 18, the axial stress shown on the ordinate axis is solely due to the applied axial load and does not include axial stresses due to pressure in the closed end configuration.

---

2. Hill, R., The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1956.

REFERENCES

1. Chu, Shih-Chi, Inelastic Behavior of Thick-Wall Cylinders Made of Strain Hardening Materials, Rock Island Arsenal Report RE7110, U. S. Army Weapons Command, Rock Island, Illinois.

2. Hill, R., The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1956.

3. Smith, J. O. and Sidebottom, O. M., Inelastic Behavior of Load-Carrying Members, John Wiley and Sons, Inc., New York, 1965.

ACKNOWLEDGMENT

This work was supported by U. S. Army Weapons Command, Science and Technology Laboratory, Rock Island, Illinois, and their help is gratefully acknowledged.

Table 1. Material Properties

	Specimen	Modulus of Elasticity, E	Poisson's Ratio, ν	Strain Hardening Factor, α	Strain Hardening Factor, $\bar{\alpha}$
Tensile Tests	S1	28.6×10^6	.27	.014	--
	C1	16.3×10^6	.36	.006	--
	C2	15.8×10^6	.33	(1)	--
	S2	29.0×10^6	.28	.001	--
	C3	17.6×10^6	.36	.007	--
	S3	--	--	.004	.004
	C4	--	--	.001	.001
Thin Wall Tests	Copper	--	--	.24(3)	.46(3)
	Steel	--	--	.016(2)	.014

(1) Specimen necked
(2) Using σ_θ, ε_θ. Also axial strain went compressive near end of test.
(3) Based on data just before failure. Very large plastic strain did not occur.

TEST MODE

1. CLOSED END WITH TENSILE LOAD.... AS SHOWN

2. CLOSED END.....REMOVE TEST MACHINE ADAPTERS

3. OPEN END..... REPLACE TEST MACHINE ADAPTERS WITH UNTHREADED PLUGS

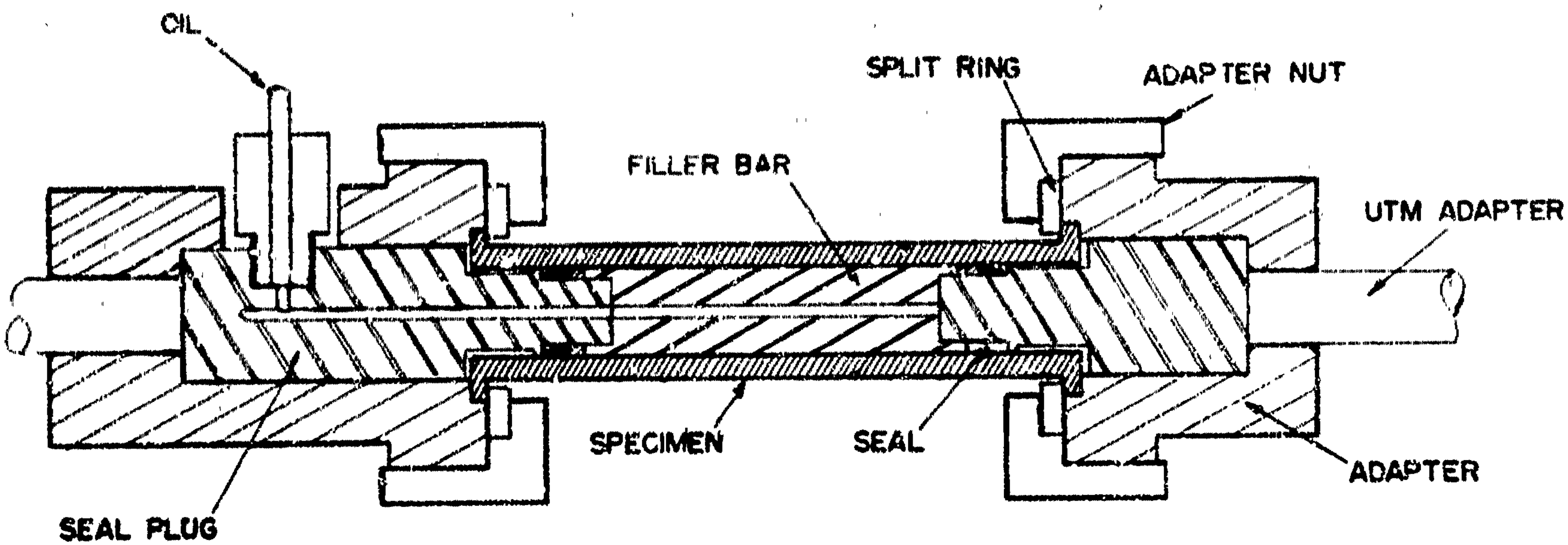
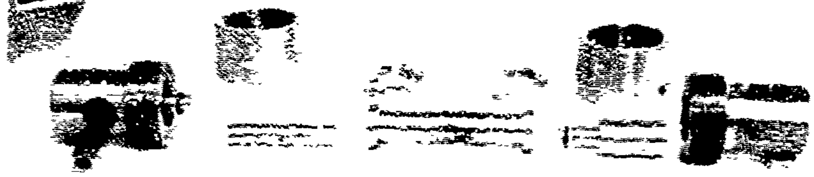
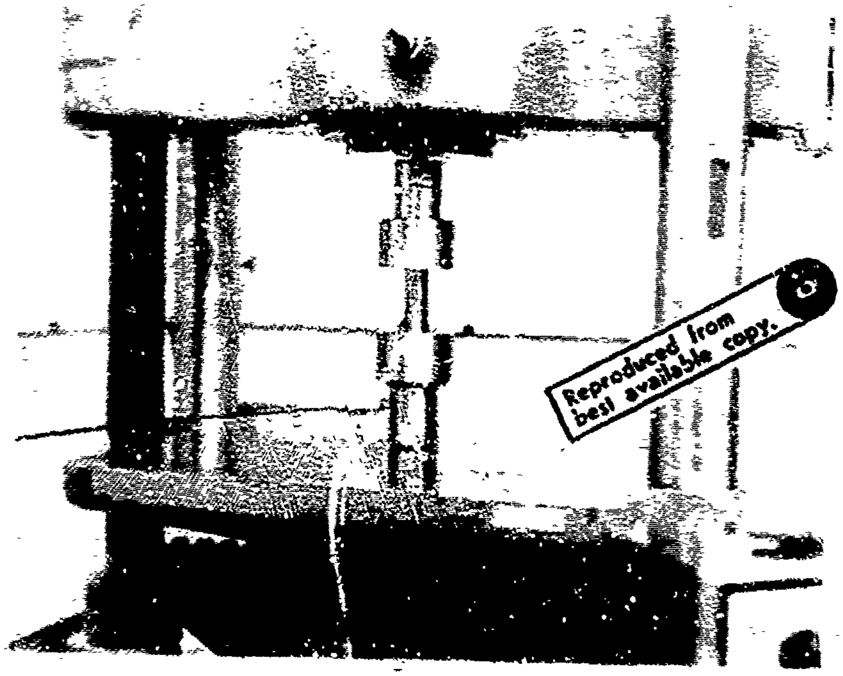


Figure 1. Specimen Test Concept





Reproduced from best available copy.

Figure 3. Test [illegible] Specimen in Open End Configuration

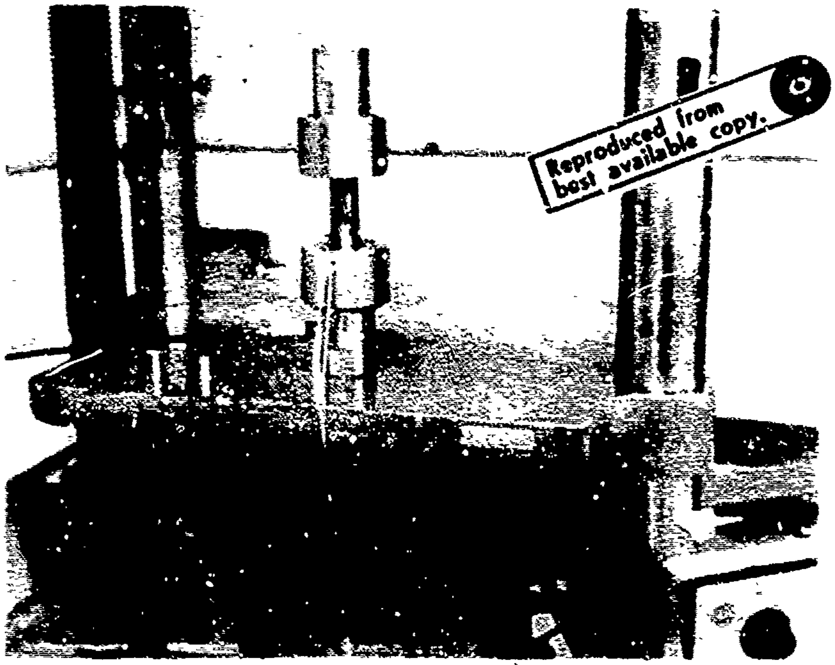


Figure [illegible]. [illegible]

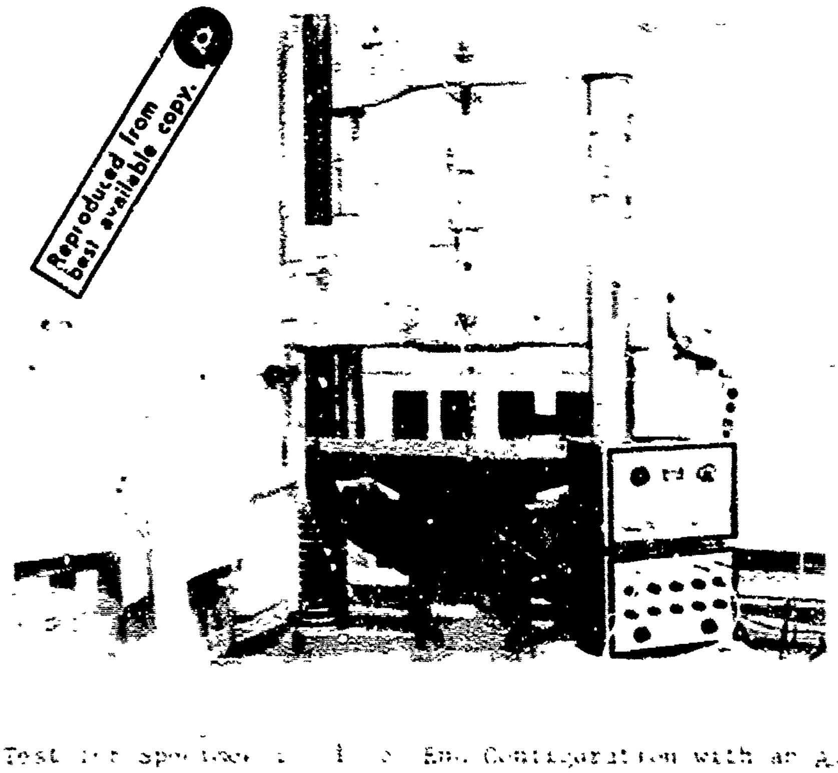


Figure [illegible]. Test [illegible] Specimen [illegible] End Configuration with an Axial L[illegible]

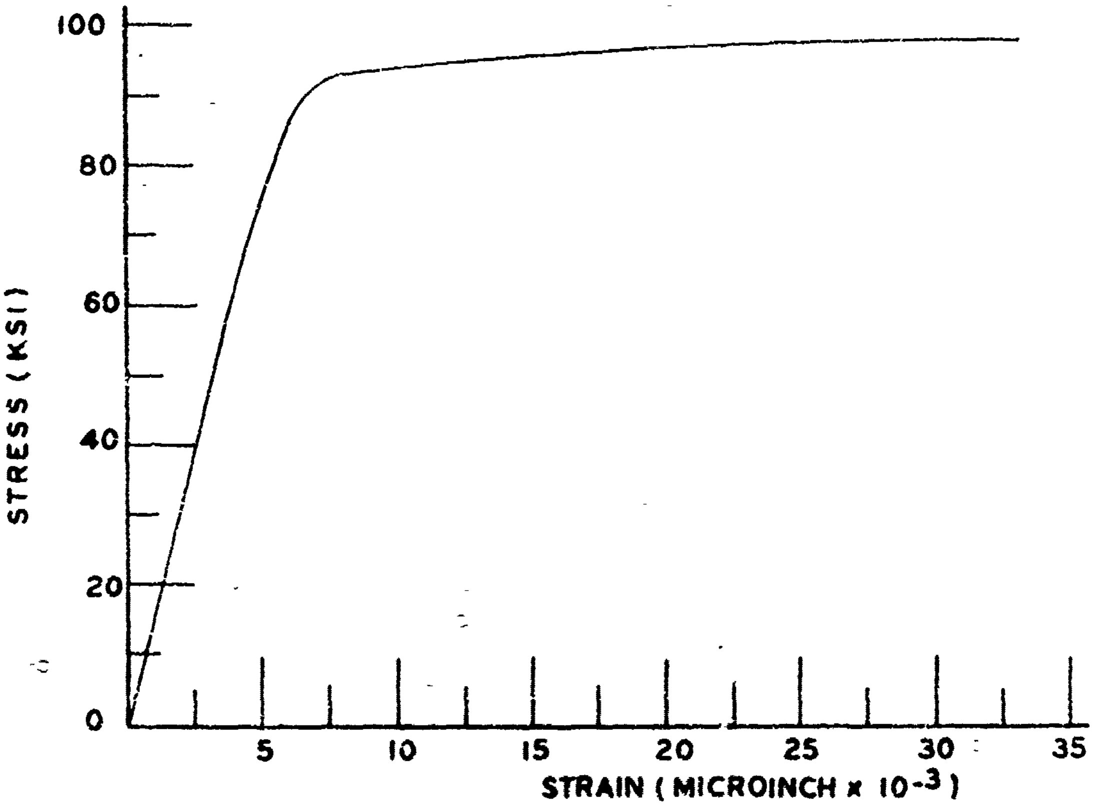


Figure 6. XY Plotter Results, Steel Tensile Specimen, S1

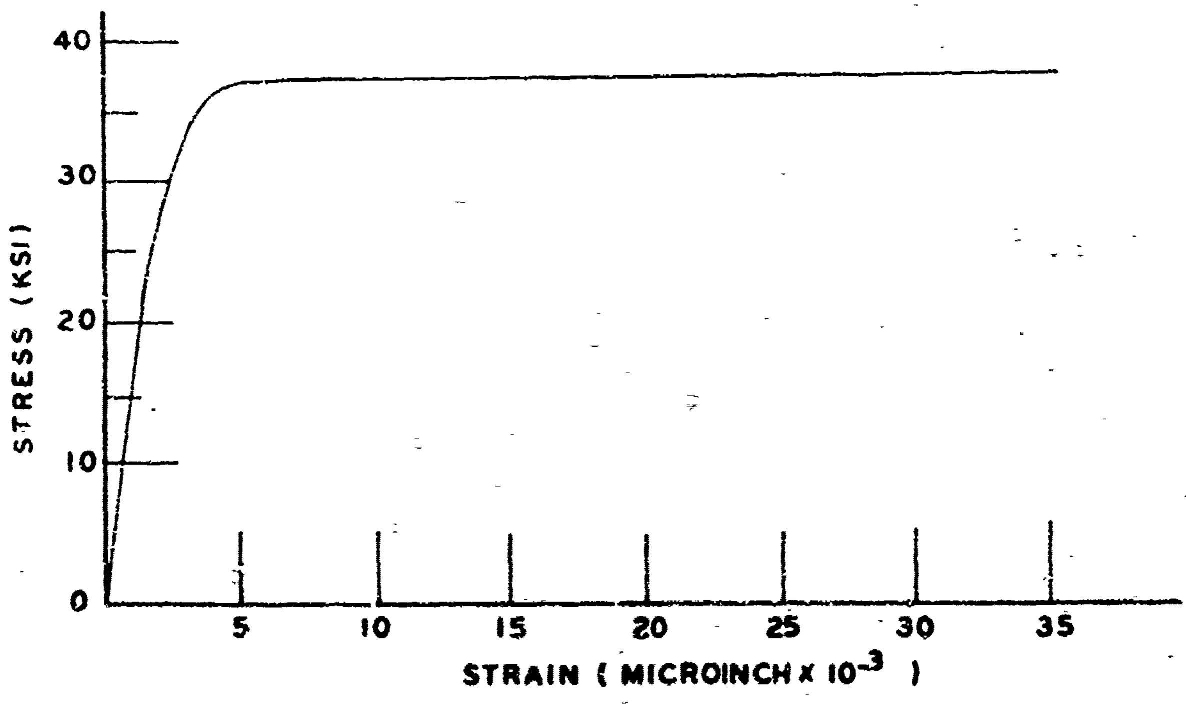


Figure 7. XY Plotter Results, Copper Tensile Specimen, C1

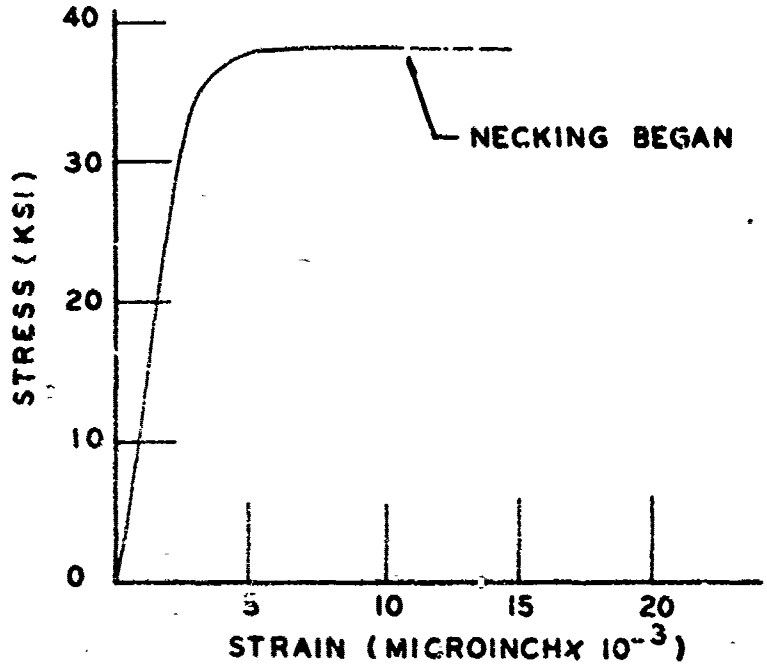


Figure 3. XY Plotter Results, Copper Tensile Specimen, C2

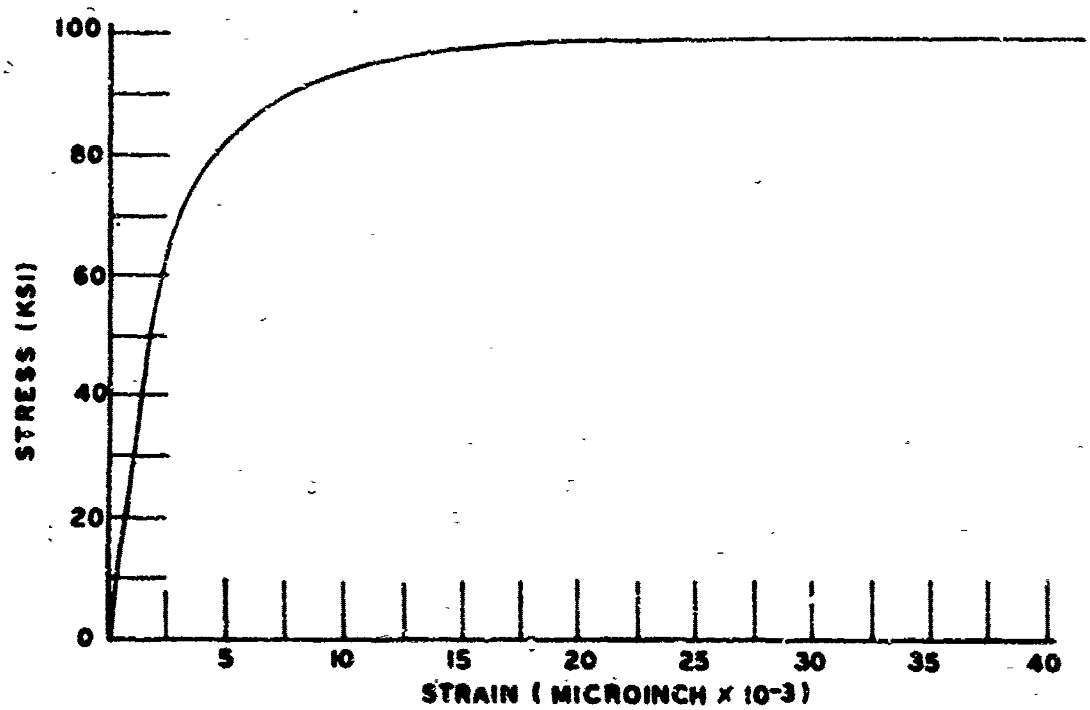


Figure 9. XY Plotter Results, Steel Tensile Specimen, S2

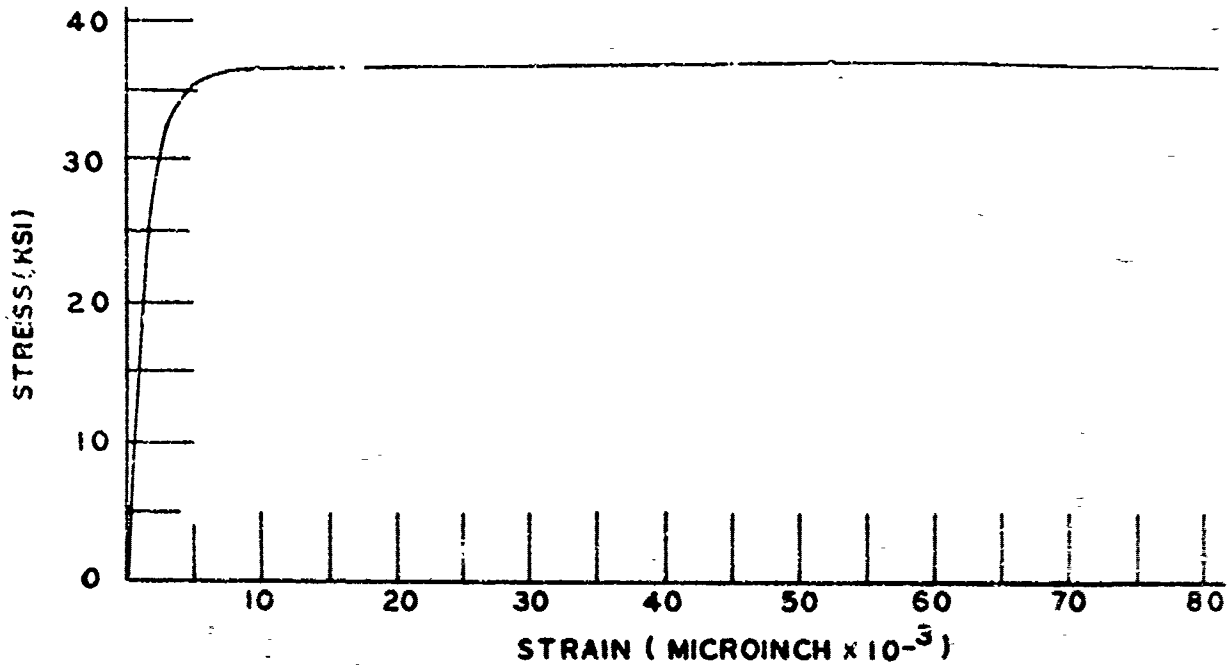


Figure 10. XY Plotter Results, Copper Tensile Specimen, C3

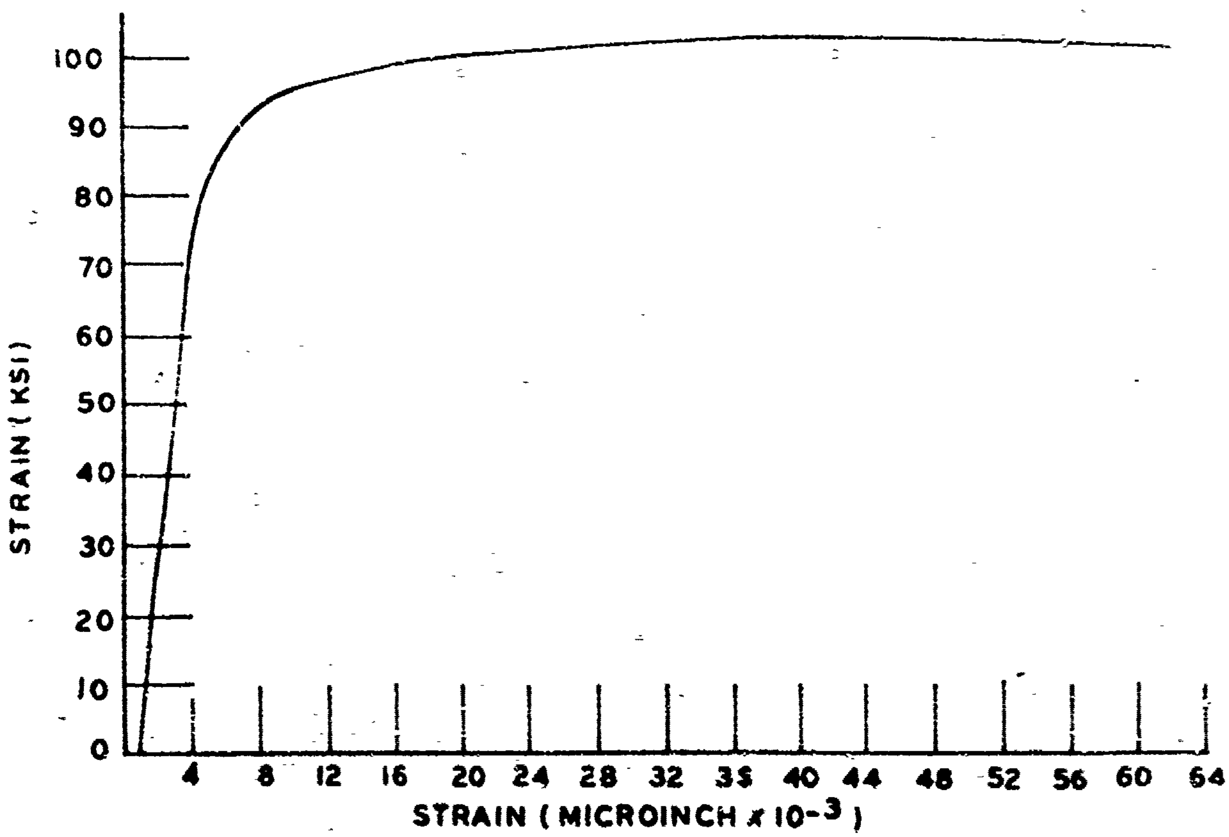


Figure 11. Recorder Results, Steel Tensile Specimen, S3

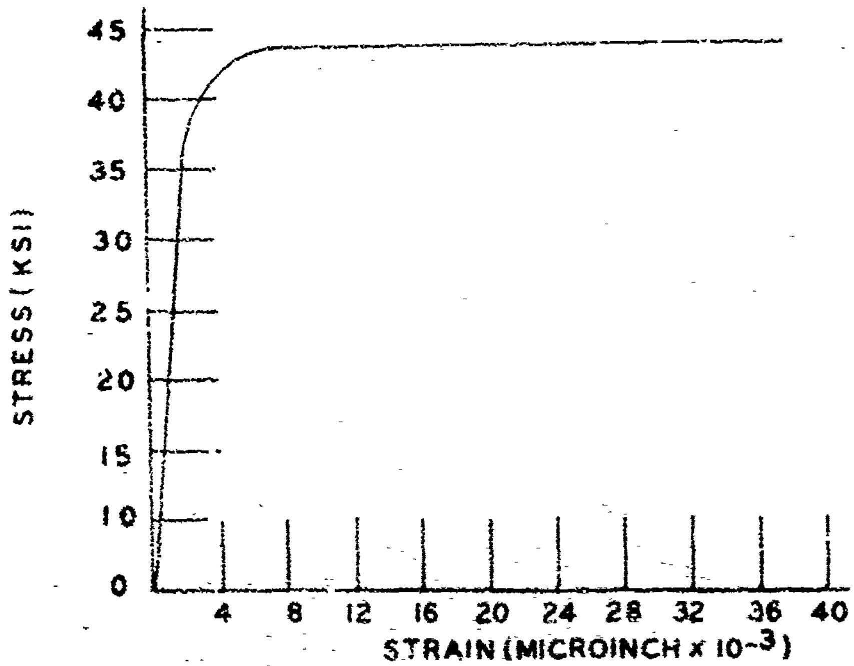


Figure 12. Recorder Results, Copper Tensile Specimen, C4

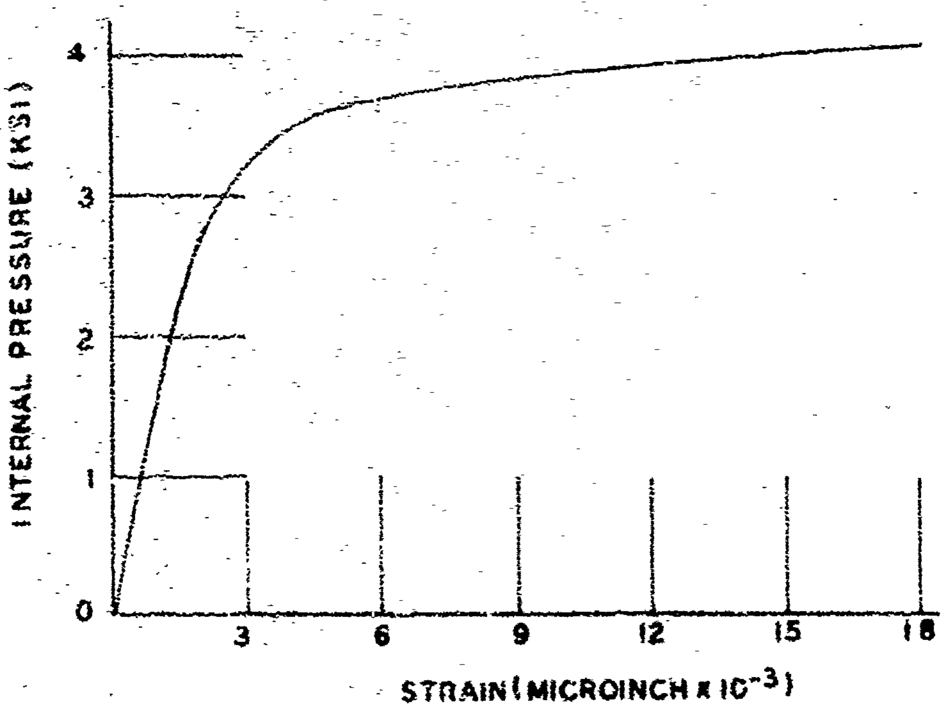


Figure 13. Steel Thin Wall Specimen

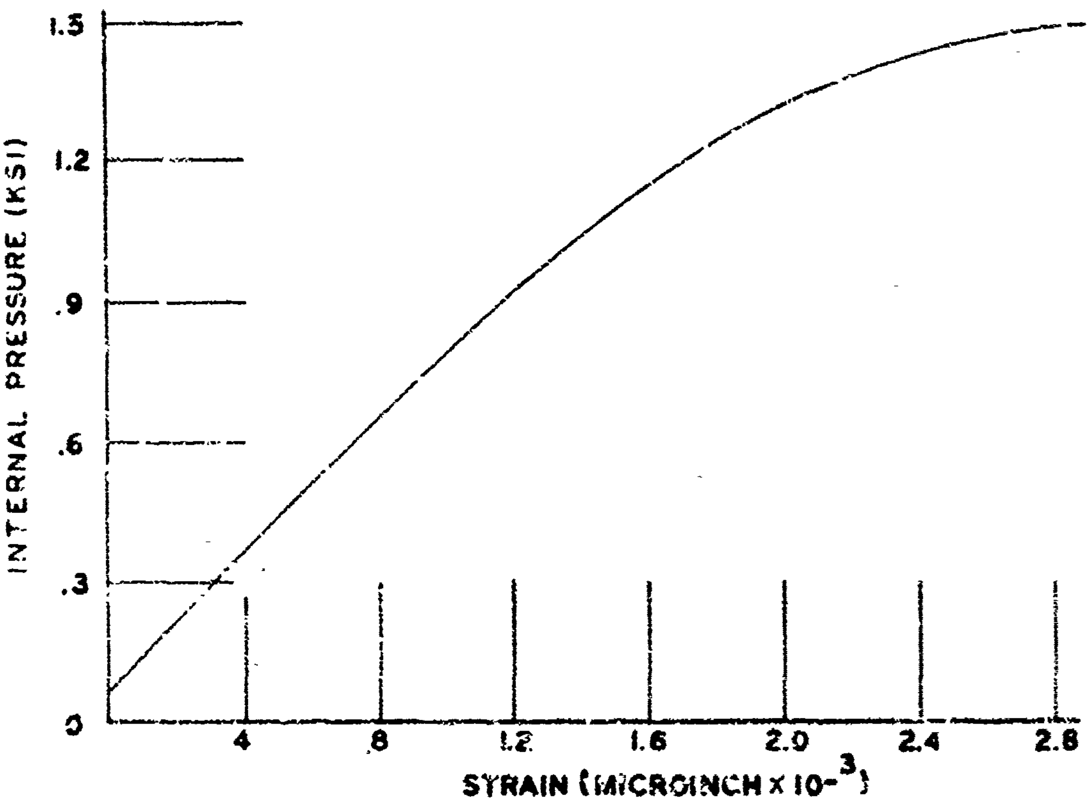


Figure 14. Copper Thin Wall Specimen

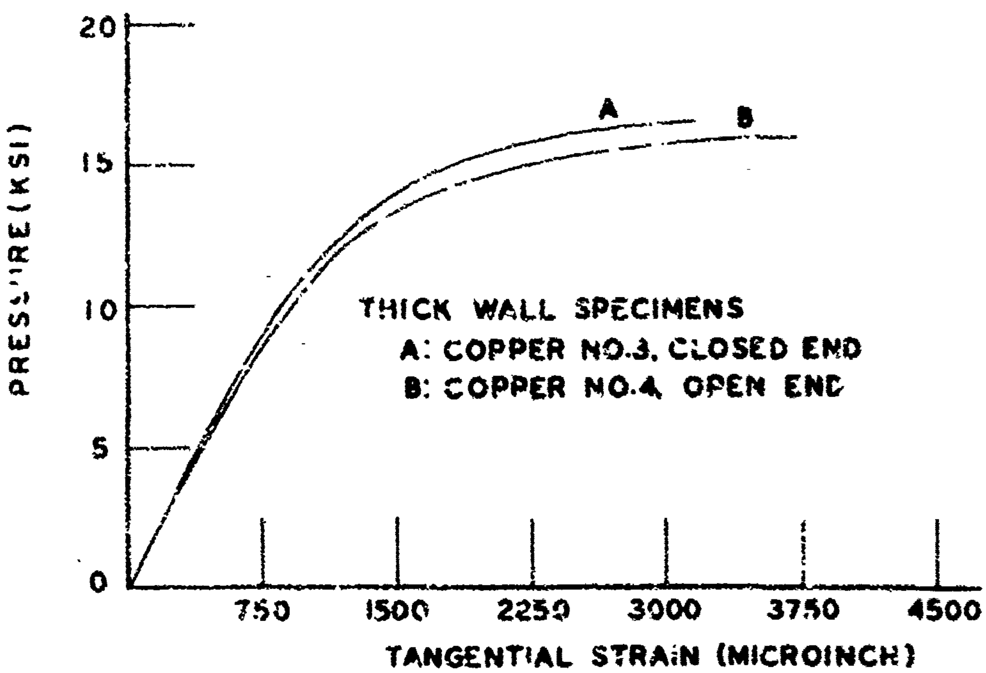


Figure 15. Copper Thick Wall Results

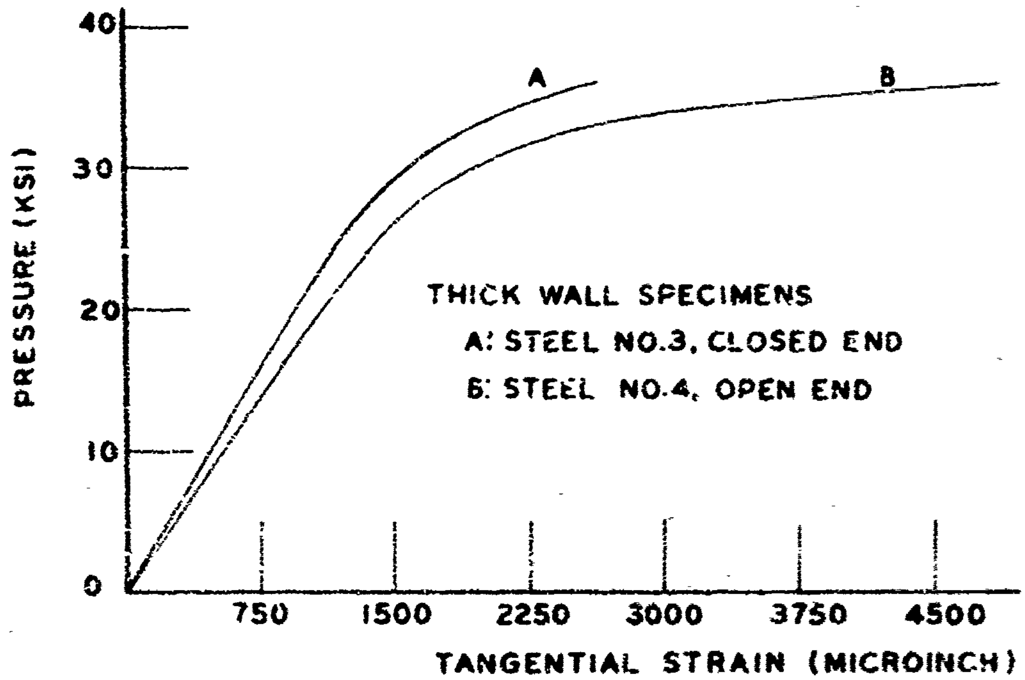


Figure 16. Steel Thick Wall Results

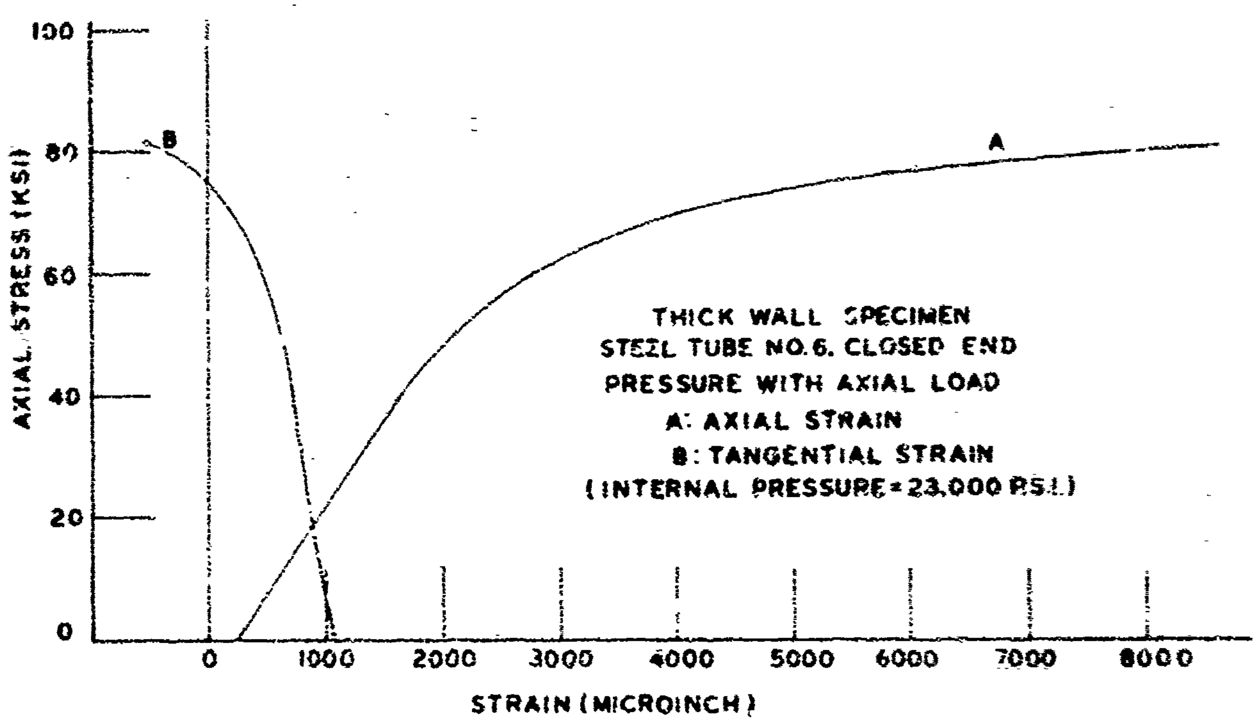


Figure 17. Steel Closed End with Axial Load

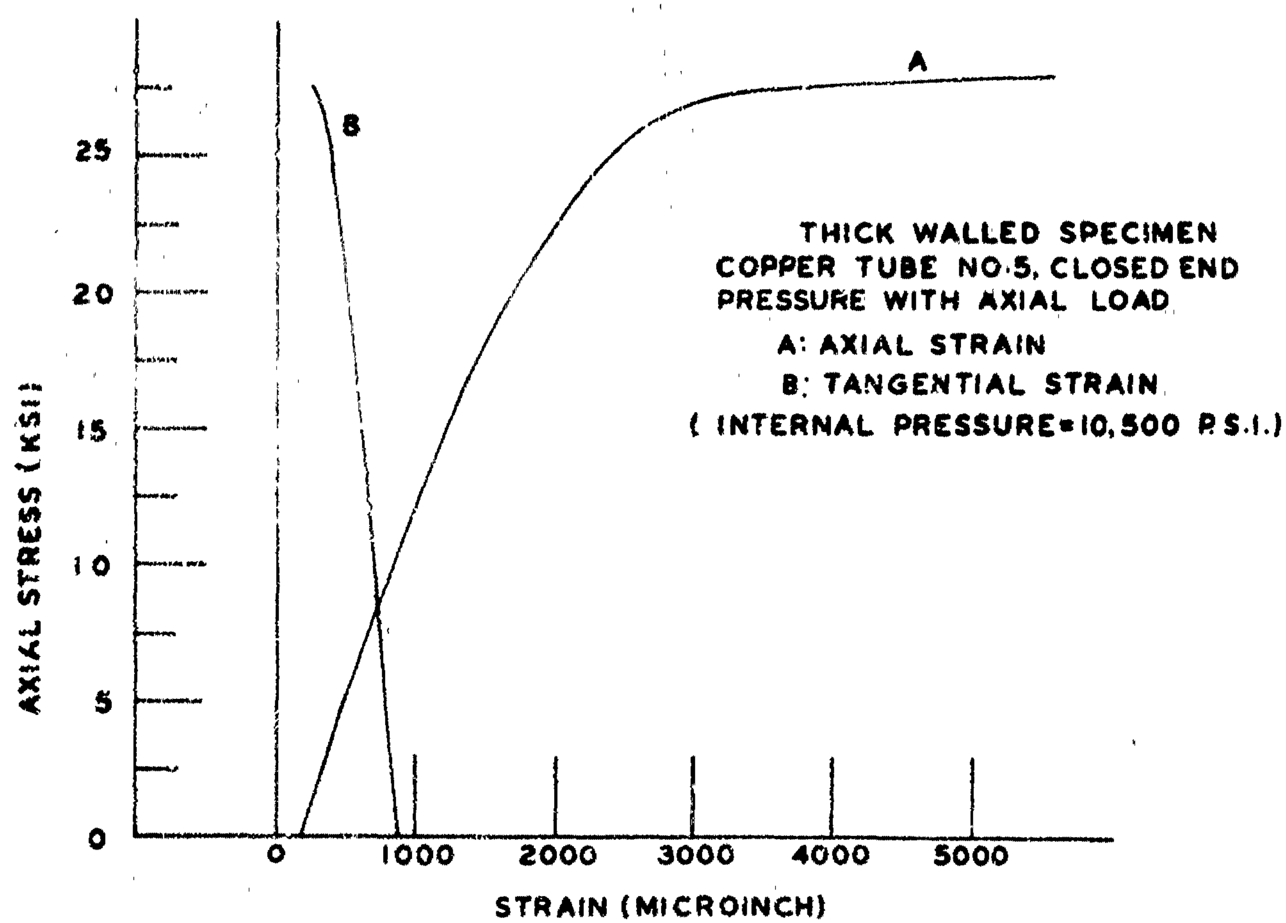


Figure 18. Copper Closed End with Axial Load